# 21. Carrock Fell: *a* Study *in the* Variation *of* Igneous Rock-Masses.—Part I. The Gabbro.

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[Plates XVI. & XVII.]

Contents.



## 1. Introduction.

During the last two years I have devoted some attention to the igneous rocks of Carrock Fell and the hills west of that well-known summit. Occurring in a somewhat critical situation on the border of the English Lake District, they were examined by Mr. J. E. Marr and myself, partly with reference to their bearing on the general geology of the district; but, apart from this, they offer in themselves some features which are of sufficient interest to be worthy of record. I have had the advantage of my colleague's co-operation, more especially in the field-work, and take this opportunity of acknowledging my indebtedness to him.

The earliest connected account of the Carrock Fell rocks was given by the late Mr. Clifton Ward[1] in 1876. He recognized three general types of igneous rocks in the district:—

(*a*) Spherulitic felsite of Carrock Fell and Great Lingy;
(*b*) Diorite (?) of Miton Hill and Round Knott;
(*c*) Hypersthenite of Mosedale Crags and Langdale.

He gave a brief account of their characters in the field and under the microscope, with chemical analyses of the first and last, and put forward a view of their mutual relations and mode of origin. In his opinion the several types pass into one another in the field, and he regarded them as produced by the metamorphism of part of the volcanic series, on the strike of which they occur.

Dr. C. O. Trechmann,[2] in 1882, pointed out that the dominant pyroxene in the so-called hypersthenite is not hypersthene, but diallage, and the rock would therefore be more correctly described as a gabbro.

Mr. J. J. H. Teall,[3] in 1885, briefly noticed the spherulitic felsite of Carrock Fell as a typical example of a granophyre in the sense

[1] Quart. Journ. Geol. Soc. vol. xxxii. (1876) pp. 16–27.
[2] Geol. Mag. 1882, pp. 210–212.
[3] *Ibid.* 1885, p. 109.

of Rosenbusch. Later he described both this rock and the gabbro (a quartz-bearing variety), stating that the one passes into the other by insensible gradations.[1]

In 1889 Mr. T. T. Groom[2] pointed out the occurrence on Carrock Fell of another type of rock, a tachylyte, in thin veins, cutting the gabbro, but considered to be connected with it. The same writer reasserted the existence of all transitional stages between the acid granophyre and the basic gabbro, and this passage seems to have been generally accepted.[3]

The references here given cover all the contributions of importance dealing with the subject of this paper since the early writings of Otley, Sedgwick, and others. Ward's work is embodied in the map of the Geological Survey.[4] He showed that rocks answering to the chief types which he recognized in Carrock Fell occur to the west as far as Roughten Gill. The sketch-map which accompanies the present paper (Pl. XVI.) differs from his as regards the boundaries of some of these intrusions; but in some parts, *e. g.* north and north-west of Carrock Fell itself, the want of exposures makes any precision impossible. This, however, does not affect the objects of the present study.

Carrock Fell itself is made up of an acid rock, which we may call 'granophyre,' since it usually shows very beautifully the granophyric structure of Rosenbusch. A similar rock is found beyond the concealed ground to the north-west, at Rae Crags; also at the head of Brandy Gill. From the latter place the rock is probably continuous, though never seen clearly *in situ*, to the exposures in the upper part of Roughten Gill and its feeders. Intrusions of granophyre, probably of the nature of minor offshoots, are also seen in Arm o' Grain and Thief Gills.

The other of the two chief rocks to be distinguished, which will be spoken of as the 'gabbro,' is seen south of Carrock Fell, as far as Mosedale village, and extends westward to Brandy Gill and Arm o' Grain, where the exposures in the gills show it alternating with the granophyre. A similar rock occurs in Roughten Gill and also higher up, in Thief Gills, where, however, it is much decomposed. The southern boundary of the main body of gabbro, from Mosedale village to Brandy Gill, is certainly, as surmised by Ward, a faulted one. The line between the gabbro and the granophyre runs from the upper part of Furthergill in a W.N.W. direction to a point about 200 yards east of Round Knott. Despite the alleged transition, which I shall discuss below, there is no difficulty in fixing this line sharply, wherever exposures occur; but it may be noted that a north-and-south traverse across Furthergill crosses alternations of the two rocks, which are naturally explained as due to offshoots of the newer one penetrating the older.

[1] 'British Petrography,' 1888, p. 178.
[2] Quart. Journ. Geol. Soc. vol. xlv. (1889) pp. 298–304.
[3] See, for example, Zirkel, 'Lehrbuch der Petrographie,' 2nd ed. 1893, p. 781.
[4] England and Wales, 101 N.E. (New Series, 23). This map is dated 1890, but was not apparently issued to the public before 1893.

If the line between the main masses of gabbro and granophyre be prolonged westward past Round Knott, it divides the gabbro which ranges west of Iron Crags from the rock of Miton Hill, etc., Ward's dubious 'diorite.' To this title the rock has no claim, containing no hornblende except some of secondary formation, and it will here be named 'diabase.' For reasons which will appear in the following pages, I concur in regarding this as belonging to a separate intrusion, distinct from the gabbro to the south; but such a separation could not confidently be made on lithological grounds alone. In both rocks the texture is very variable. The rock on Miton Hill itself often assumes the coarsely crystalline characteristic of a gabbro, while many specimens from the crags in the gabbro-area would, if taken apart, be designated 'diabase.' The names will be employed, with this explanation, to emphasize the distinctness of the two intrusions and to mark their dominant characters. The diabase is cut off to the north by a fault seen in the southerly branch of Drygill, but it probably extends eastward under the much-obscured ground north of Carrock Fell.

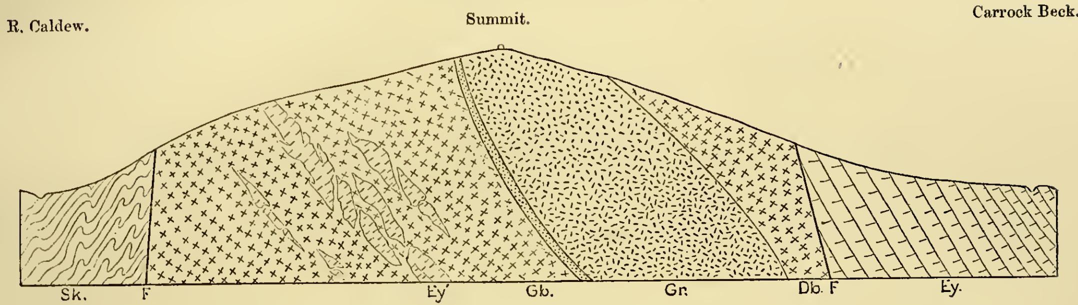
In addition to the above rocks, I hope to notice in a future communication a very interesting one which is seen at the junction of Brandy Gill with Grainsgill and in the adjacent hillsides. It is only incidentally mentioned by Ward as "a very quartzo-micaceous granite." It is, indeed, a 'greisen,'[1] and is so named on the Geological Survey map, where its boundary is indicated. This rock is, as will be shown, connected with the Skiddaw granite, and has probably no relation with the Carrock Fell intrusions.

Excluding the rock last mentioned, and taking the others as a whole, they are intruded, as is shown on the Survey map, among that part of the great Ordovician volcanic series which is conveniently known as the Eycott Hill group, a group consisting essentially of a succession of basic lavas. These lavas can be followed along a curved and broken line of strike from Eycott Hill to Carrock Fell, and they possess unique characteristics which place their identity beyond doubt. No junction of the intrusive rocks and these lavas is exposed along the northern line of boundary, although the Eycott rocks are seen at Clints Gill, etc., penetrated by small dykes and veins of granophyre. Along the southern boundary the gabbro is faulted against Skiddaw Slates. Mr. Ward states that the latter are "much altered," an expression which seems stronger than the appearances warrant. A certain degree of alteration may be granted, but it is doubtful how far this is connected with the gabbro. Tracing the Skiddaw Slates up the Caldew valley towards the granite and greisen, we find mere induration giving place to 'spotted' rocks, and these in turn to highly metamorphosed types ('mica-schists') to which Ward's description "much altered" well applies; but near Mosedale, where the effect of the gabbro can be tested apart from the disturbing element of the granitic intrusions, the alteration of the slate is not great. As regards the effect of the

[1] This rock was briefly noticed by me in 'The Naturalist' for 1889, p. 209.

*Diagrammatic Section across Carrock Fell.*

[Scale 3 inches = 1 mile.]




Gr. = Granophyre.
Db. = Diabase.
Gb. = Gabbro.
F = Faults.

Sk. = Skiddaw Slate.
Ey. = Eycott Volcanic Group.
Ey' = the same, highly metamorphosed.

fault, there must be a considerable downthrow to the north, but there is reason to believe that very little of the gabbro is lost by the break.

Both granophyre and gabbro form steep cliffs to the eastward, facing the alluvial flat of the Caldew, and they make no further appearance in that direction. This is probably due to their natural termination, and not to any fault. It is certain, at least, that the Eycott lavas come up to the intrusive masses on this side, for they are seen in the face of the gabbro cliff and on the heights above. The relations are not those of a simple junction of the intrusive rock with the lavas along a definite line. As one climbs up the cliff, *e. g.* at Snailshell Crag, sometimes gabbro, sometimes lava is seen, or the two together in intricate association, making it clear that large portions of lava have been enclosed by the molten gabbro. The same relations are shown at the top of the cliff, and the Eycott rocks occupy much of the ground along a W.N.W. line from here to Iron Crags, a distance of a mile or more. They are not continuous, but occur in large detached patches embedded in the gabbro and penetrated by countless veins of that rock. They give the idea of having been partly buoyed up by the molten gabbro-magma, which nevertheless welled up in every crack that was formed. A comparison of these phenomena with what is seen in the cliff near Snailshell Crag and Black Crag shows that the lavas must pass right into the gabbro-mass in the direction named, which is that of their strike. The remnants which are seen, embedded in gabbro, between Mosedale and Iron Crags are highly metamorphosed, but still easily recognized. The well-known and beautiful porphyritic lava (No. 4 of Ward's section[1]), the less markedly porphyritic lavas which succeeded it, and certain tuff-beds are clearly distinguished, and, what is more remarkable, they seem to occur in their proper order, and certainly follow their normal strike. It appears that the gabbro, forced in probably along the base of the Eycott group, has not only disturbed and lifted the lavas, but in some measure bodily engulfed considerable stretches of them. The Eycott group in this district has a very steep dip to N.N.E., and the mass of gabbro seems to have a similar inclination. Whether at the time of the injection the volcanic rocks lay more nearly horizontally is not evident from the mapping. I have found no lavas associated with the granophyre or the diabase. The remarkable patches of Eycott lavas enclosed in the gabbro did not escape the notice of Mr. Ward, who noted the occurrence of 'trap in hypersthenite' in the neighbourhood of Mosedale. I cannot, however, endorse his statement that the one rock passes into the other; the junction of the two is always of such a nature that both rocks can be clearly exhibited in one microscopical slice. The supposed transition was one of the grounds on which he based his suggestion of a metamorphic origin for the gabbro and its associated rocks.

The geological relations of the diabase need not be discussed at this point. I shall show reasons for believing that its intrusion

[1] Monthly Microsc. Journ. vol. xvii. (1877) p. 241.

followed that of the granophyre, while that of the gabbro preceded the acid intrusion. It may be remarked that numerous dykes or veins of granophyre similar to the rock of Carrock Fell occur in the gabbro to the south, but I have not found any of these in the area mapped as diabase. It can scarcely be doubted, however, that the three rocks belong to the same general period of igneous activity, and with them we may include in this statement the numerous basic dykes and veins, of which Mr. Groom's rock is one. These dykes were injected after all the larger igneous masses, for they are found cutting gabbro, granophyre, and diabase alike. The geological age of this complex of igneous rocks is a question which may be deferred for the present.

The greisen of Grainsgill is probably quite distinct from the preceding rocks. It must be referred, with the more normal type of the Skiddaw granite, to a late phase of the great post-Silurian disturbances. It is intrusive in Skiddaw Slates, and produces in them an extraordinary degree of metamorphism.

In the present communication the gabbro alone will be treated in detail, the granophyre, the dykes of Carrock Fell, and the greisen of Grainsgill being reserved for further treatment.

## 2. Mineralogical Characters of the Gabbro.

Before describing the remarkable variations of the gabbro in different localities it will be convenient to mention the minerals which compose the rocks. A triclinic felspar and a monoclinic pyroxene are essential to all the varieties, though their relative proportions may vary considerably. Quartz and iron ores become prominent constituents in the more acid and the more basic types respectively. Besides these, there are accessory and exceptional minerals and those of secondary origin.

The felspar occurs for the most part in idiomorphic crystals, which, in fresh specimens, are quite clear. They always show albite-lamellation, and usually Carlsbad twinning in addition, while pericline-lamellæ occasionally come in somewhat capriciously in portions of the crystals. The albite-twinning is sometimes inconstant or interrupted, but there is nothing to prove decisively that it is in general of secondary origin, although secondary lamellations, both albite and pericline, are found locally; see Pl. XVII. fig. 2. Sections perpendicular to the lamellæ give extinction-angles up to about 32°, indicating a basic variety of labradorite. The specific gravity is a little under 2·69. It is a point of some theoretical importance that the same variety of felspar is found in specimens of the gabbro differing widely in chemical composition. Only in some of the most highly basic rocks does the felspar sometimes show larger extinction-angles, indicating an approach to anorthite. On the other hand, in some of the more acid quartz-bearing rocks the border of a crystal gives a very slightly lower extinction-angle than the main portion, indicating that the outer layers are a

little more acid. This zonary structure seems, among plutonic rocks, to be specially characteristic of those which, without being true acid rocks, have developed free silica as the last stage of consolidation. Rosenbusch has remarked the general absence of zonary structure in the felspars of ordinary gabbros.

The felspar is, as a rule, though not invariably, of earlier crystallization than the pyroxene, and thus, while the latter mineral never builds very characteristic ophitic plates, the structure of the rock approaches that of a diabase. In view, however, of its coarse texture and of the peculiarities of the pyroxenic constituent, I have preferred to retain the name 'gabbro' used by other writers.

The dominant pyroxene, as remarked by Dr. Trechmann, is certainly a monoclinic one. It rarely shows any crystal boundaries, but occurs in allotriomorphic plates and wedges. The colour is of the light greyish-brown tone so frequent in diallage and salite, and there is no sensible pleochroism. Besides the well-marked prismatic cleavage, there are occasional indications of others parallel to the orthopinacoid and clinopinacoid. Simple twinning on the usual law, parallel to the orthopinacoid, is not infrequent, but this rarely gives rise to repeated lamellation. The most conspicuous feature of the mineral is a very delicate lamellation parallel to the basal plane, often marked by a certain amount of 'schillerization.' In a clinopinacoidal section the structure makes an angle of about 75° with the cleavage-traces, and if the crystal be also twinned on the usual law a very characteristic 'herring-bone' appearance results. (See Pl. XVII. fig. 1.) This has been figured by Mr. Teall[1] from the Whin Sill, a rock having several special features in common with the Carrock Fell gabbros. The characters of our pyroxene thus connect it with salite rather than with diallage; but, as the analyses of the rocks show that the mineral is rich in alumina, I shall speak of it as augite.

The most usual secondary alteration of the augite is that which results in a rather fibrous hornblende of a pale yellowish-green tint. The change begins at the margin of a crystal, and spreads to the interior, the augite and hornblende always having the usual crystallographic relation to one another. The completed pseudomorph still shows the orthopinacoidal twinning and the basal striation with its incipient schiller-structure. Small patches of brown hornblende in the interior of the fresh pyroxene seem to represent an original intergrowth, but these are of quite exceptional occurrence. Brown biotite, apparently a highly ferriferous variety comparable with haughtonite, is a frequent accessory constituent of the gabbro, but seems to occur only in special circumstances, which will be noticed below.

Although the original identification of hypersthene seems to have been erroneous, it is probable that a subordinate rhombic pyroxene was originally present in parts of the gabbro. Such is the most likely interpretation of certain pale green, fibrous pseudomorphs seen

[1] Quart. Journ. Geol. Soc. vol. xl. (1884) p. 647, pl. xxix. fig. 2.

in some slides. These occur more plentifully in some intrusions near Haweswater, such as that which forms Walla Crag. Of olivine I have found no certain trace, even in the most highly basic variety of the gabbro. This mineral seems to be unknown in the Lake District, except in a few minor intrusions such as that of Little Knott.

The presence of quartz in the Carrock Fell gabbro has long been known. It occurs sometimes in interstitial grains, but more frequently as a constituent of micropegmatite filling the interspaces between the augite and felspar-crystals. The intergrown felspar is probably in part orthoclase, the analysis showing a certain amount of potash in the rocks. The micropegmatite is a prominent constituent in the most acid gabbro, and is tolerably plentiful in many examples in which the silica-percentage must be quite low, failing completely only in the very basic varieties. (See Pl. XVII. fig. 3.)

Apatite, in rather stout prisms, is capriciously distributed. In many slides it is wanting, but it occurs in both acid and basic varieties of the gabbro, and in the latter sometimes rather abundantly. Grains of sphene are seen in some slides, but their form and their association with the iron ores are such as to suggest a secondary origin for the mineral.

Opaque iron-ores are very sparingly present in the most acid variety of the rock, but become increasingly abundant in the more basic examples, and in some form a very important part of the mass. In one case nearly 25 per cent. of the finely powdered rock was extracted by a horseshoe magnet. These rocks, very rich in iron ores, strongly attract the magnetic needle, but they show no evident polarity and do not orient themselves when freely suspended. The iron ores are in the main among the earliest products of crystallization in the gabbro, but they do not, as a rule, show any perfection of crystal outline. Viewed in reflected light some of the crystal-grains show a black or bluish-black colour, while others have a tinge of grey. The former only are attacked by cold hydrochloric acid. It appears, therefore, that we have both magnetite and ilmenite present, and the chemical analyses given below confirm this conclusion. In some places a crystal-grain consists partly of one, partly of the other mineral, with crystal-faces common to the two and a dividing line like a twin-line parallel to a crystal-boundary. (See Pl. XVII. fig. 5.) This is an arrangement which does not seem to be common in other rocks. Further, there are not wanting here indications of a more minute intergrowth of the two iron-ore minerals, and the colour of some grains leaves doubt whether they should be referred to magnetite or ilmenite. It is worthy of notice, too, that apparently almost the whole of the iron ore in the rock is magnetic. More precise knowledge concerning 'titaniferous magnetite' and 'titanomagnetite' seems desirable.

Pyrites is only locally present in the very basic gabbros (Arm o' Grain, etc.).

### 3. Minor Textural and Mineralogical Variations.

The remarkable differences, apparent to the most casual observer, among specimens collected from the Carrock Fell gabbro area are due to the coexistence of different kinds of variation, which must be considered separately. I shall distinguish:—

(i) Minor variations in texture, and sometimes in mineralogical constitution, usually on a small scale, following certain directions of banding, or without any evident arrangement;

(ii) Wide variations in chemical composition, and consequently in mineralogical constitution, having a definite relation to the form of the intrusive mass as a whole;

(iii) Strictly local modifications, forming part of a reciprocal metamorphism between (*a*) gabbro and enclosed masses of lava, or (*b*) gabbro and granophyre.

These will not all be discussed at equal length. The first and second are jointly answerable for the great dissimilarity between specimens collected from different spots, and of these the second is of greater interest.

I have already alluded to the variability in texture of the gabbro. As seen in the field, the change from coarse to fine grain is often rather abrupt. Sometimes the two are associated in a quite irregular manner, or patches of coarser rock occur embedded in finer. Such contrasts are seen not only on a small scale, but also between adjacent portions of gabbro, perhaps 100 yards across. In other places rocks of different textures are associated in alternating thin layers, simulating stratification, and slight differences in durability produce a fluted aspect on a weathered face. Ward appealed to this peculiarity in support of his theory that the gabbro represents metamorphosed volcanic rocks, but such an idea is, for many reasons, quite untenable. The phenomenon, indeed, is a very common one, and must be familiar to most geologists who have studied gabbros or other basic rocks.[1] It presents a rather perplexing problem, and suggests that some factor not yet fully appreciated has had some determining influence on the crystallization of such rocks. The banded structure of rhyolites, where crystalline or spherulitic layers alternate with glassy, has been explained by Iddings[2] as depending upon the different proportions of water contained in different parts of the magma, which were drawn out in the direction of flow, but such an explanation could have no application in the present case. I shall give evidence to prove that the gabbro-magma had very little viscosity when it was intruded, and that diffusion was able to operate through it after the intrusion, so that the banded structure can scarcely be taken to

[1] For remarks on this point, see G. H. Williams on the gabbros of Maryland, Bull. 28 U.S. Geol. Surv. vol. iv. (1886) pp. 25, 26, and A. C. Lawson on the anorthosites and gabbros of Canada, Neues Jahrb. Beil. Bd. viii. (1893) pp. 448 *et seqq.* [See also the paper by Sir A. Geikie and Mr. Teall, which is to be published in the present volume, where additional references are given.]

[2] Amer. Journ. Sci. ser. 3, vol. xxxiii. (1887) pp. 43–45.

indicate lines of flow. This structure seems to be quite independent of the more general variation in the gabbro-mass as a whole, which I shall describe below. At several localities the banding was observed to dip steeply to N.N.E., which agrees with what seems from other evidence to be the lie of the intrusion as a whole. Near Round Knott, however, there are lower and undulating dips, often southerly. In most parts of the gabbro no banding is observable.

The finer-textured portions of the gabbro have in the field a generally darker look than the coarser parts, which seem more felspathic. This—a common observation in such rocks—is perhaps in part illusory. There are, however, considerable local variations in the mineralogical composition of the gabbro, which are possibly connected with the variations in texture. Thus, at a few spots the rock is very rich in augite, the lustrous surfaces of that mineral appearing in a hand-specimen to make up by far the greater part of the whole. At no great distance this variety may be found to give place to one in which felspar and magnetite are richly represented. Gabbros are well known to be peculiarly liable to such variability, which does not necessarily import any very great difference in chemical composition between the several varieties. The felspar and augite probably do not differ much in silica-percentage, while the iron which goes into the pyroxene in one case goes into the magnetite in the other, the chief differences being probably in the alumina and soda. However this may be, the essential differences which these irregular mineralogical variations denote are certainly far less than those to be discussed next, which have a definite arrangement and an important significance. An account of these wider and more general variations will show conclusively that the gabbro represents a single intrusion of igneous magma, which was all thoroughly fluid at one time; so that the abrupt local changes and banded structure cannot be explained as the results of successive interlacing injections.

### 4. Orderly Variation from Centre to Margin.

Apart, then, from minor local variations, we must remark that specimens of the gabbro from different localities show wide differences both chemically and in the relative proportions of their minerals; and a study of the rocks in the field soon shows that the more acid varieties occur in the central part of the mass, the more basic near the edge. Two chemical analyses from different localities are given below: besides these I have had several silica-percentages kindly determined for me by Messrs. W. A. Brend and E. H. Cunningham-Craig.[1] The highest silica-percentage is 59·46 for a rock taken near White Crags; the lowest is 32·50 for the northern margin of the mass as exposed in the upper part of Furthergill Sike. The other figures obtained accord very fairly with the localities of

[1] The determinations were made by Messrs. Brend and Cunningham-Craig in the laboratory of Sidney Sussex College, Cambridge. Since writing the above, I have received the results of others made by Messrs. Boyd, Fry, Gunnell, Guthrie, King, and Peatfield, at the Yorkshire College, Leeds: these I owe to the kindness of Dr. J. B. Cohen. The two sets of figures are distinguished

the specimens, on the law that the gabbro becomes more basic from centre to margin. The mineralogical constitution of the rocks varies accordingly. The more acid rocks, in the central part of the area, have plenty of micropegmatite and scarcely any iron ore, while in the more basic rocks of the margin quartz is wanting and iron ores are very abundant, amounting in the extreme case to nearly one-quarter of the whole rock.

A very little examination of the rocks in the field is enough to convince the observer that the relatively acid and the extremely basic varieties of gabbro represent modifications of one original magma; that these extremes graduate imperceptibly into one another through intermediate varieties; and that all the varieties are arranged with striking regularity in successive zones corresponding in general form to the boundary of the whole mass. In view, however, of the great difference between the extreme types (the silica-percentage diminishing by 27 in 400 yards) and of the important deductions to be drawn from the phenomena, it is desirable to present the evidence of the continuity of the whole mass in some precise form. To obtain a large number of chemical analyses was impracticable, and I have accordingly availed myself of the density of the rocks as a rough test of their relative basicity, or, more particularly, of their relative richness in the denser minerals. This of course agrees in a general sense with the silica-percentages, the less acid rocks being the heavier; but, judging from such data as we have, the agreement does not always hold very precisely. The figures for specific gravity are found to show a much more regular distribution than those for silica-percentage. The reason for this is easily seen: the most important respect in which the several specimens differ is in their content of iron oxides, and the best test

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below by the letters S and L, respectively. I give here those which relate to the gabbro, and with them the figures from Mr. Barrow's two analyses and from that by Mr. J. Hughes mentioned in Ward's paper.

(i) White Crags:
Silica 59·46 (S); sp. gr. 2·804.

(ii) White Crags (the locality may be some distance from the preceding):
Silica 59·656 (Hughes).

(iii) 350 yds. S. of White Crags, 120 yds. W.N.W. of sheepfold:
Silica 57·7 (S); sp. gr. 2·877.

(iv) By road-side, about 150 yds. N.N.W. of Chapel Stone:
Silica 53·50 (Barrow); sp. gr. 2·800.

(v) Same locality:
Silica 50·5 (L).

(vi) 600 yds. S.W. by S. of White Crags, 200 yds. E.S.E. of sheepfold:
Silica 50·22 (S); sp. gr. 2·939.

(vii) 120 yds. N. of summit of White Crags:
Silica 47·11 (S); sp. gr. 2·848.

(viii) Top of cliff above Mosedale, southern edge of gabbro:
Silica 44·14 (S); sp. gr. 3·103.

(ix) Gill $\frac{3}{8}$ mile N.W. of Swineside, southern edge of gabbro:
Silica 43·4 (L); sp. gr. 2·952.

(x) Lower part of Furthergill, northern edge of gabbro:
Silica 33·4 (L); sp. gr. 3·200.

(xi) Upper part of Furthergill, northern edge of gabbro:
Silica 32·50 (Barrow); sp. gr. 3·265.

of this, short of actual estimation of the iron, is the density of the rocks.

The specific gravities have been determined by the hydrostatic balance on specimens usually of more than 50 grams, and so large enough to eliminate small variations: the figures are all reduced to 4° C. The mean specific gravity of specimens from forty-two different localities in the gabbro area is 2·953, and the range of variation is about 20 per cent. of this mean, the extreme figures found being 2·679 and 3·265.

If we take a traverse from north to south across the gabbro, we find the specific gravity to decrease steadily until the central zone is passed, and then to increase steadily to the other border of the intrusion. Below are the figures for three parallel traverses across the eastern portion of the area, where exposures are most frequent. Each hiatus represents a place where the rocks are concealed:—

| | | |
|---|---|---|
| 3·222 | 3·265 | 3·200 |
| 2·848 | —— | —— |
| 2·804 | 2·850 | 2·933 |
| 2·778 | 2·822 | 2·800 |
| 2·844 | 2·890 | 2·872 |
| 2·877 | 2·939 | 2·922 |
| —— | 3·110 | 3·103 |

It will be seen that, without exception, the gabbro grows denser from centre to margin in both directions. The full significance of the figures, however, is seen only when they are laid down on a map. With a sufficiently large number of observations, it would be possible to connect points corresponding to equal specific gravities by lines like the contour-lines round a hill or the isobars round a cyclonic centre. I have not attempted to go so far as this, but I consider that the figures given are sufficient to establish the continuity of the whole mass and the distribution of the several types in roughly concentric zones becoming denser from the centre to the margin of the area. The accompanying map (Pl. XVI.) shows the approximate course of lines corresponding to specific gravities 2·85 and 2·95. These arbitrarily chosen limits divide the gabbro area into three parts:

(i) A central portion of specific gravity less than 2·85: here the rocks are relatively acid, and usually contain rather abundant quartz;

(ii) An intermediate zone of specific gravity 2·85 to 2·95: consisting of more normal gabbro, in which quartz is at most an accessory constituent;

(iii) A marginal zone of specific gravity above 2·95, and in the limit very much higher: the conspicuous feature here is the great abundance of the iron ores.

Without entering into further detail, it will be taken as proved that the various types are only parts of a single body of rock, which becomes progressively richer in iron oxides (and, as we shall see, in certain other constituents) from centre to margin, and that this change is most rapid as we approach the actual boundary of the

mass. In other words, there has been, from whatever cause, a *concentration* of the iron oxides and certain other constituents in the marginal portion of the mass.

Phenomena indicating a concentration of this kind have been recorded in numerous instances from different parts of the world. Prof. Vogt[1] has recently reviewed the literature of the subject and critically examined all the leading facts; so that it is not necessary here to enter upon so wide a field. The phenomena are characteristically found in basic and ultrabasic rocks, and in extreme cases have given rise to almost pure aggregates of iron ore of undoubtedly eruptive origin. Vogt distinguishes especially an 'oxidic' type of concentration, characterized by the secretion of titaniferous iron-oxides, and a 'sulphidic' type, characterized by nickeliferous iron-sulphides. At Carrock Fell we evidently have to do with the former type. According to Vogt the titaniferous iron-oxides tend to aggregate by preference in the central part of an eruptive mass, while the nickeliferous iron-sulphides concentrate in the marginal part. As regards the former, this generalization seems to go rather beyond the facts, and the case that I am describing is emphatically opposed to it. In some of the cases which Vogt notices of aggregates of iron ores in the heart of an eruptive mass, the aggregates evidently are abruptly bounded, and their secretion from the magma must have taken place before the intrusion, so that the original relations are lost. Where a perfectly graduated transition indicates a differentiation of the intruded magma *in situ*, the enrichment in iron oxides, etc., seems to be typically a marginal phenomenon.

I now proceed to examine more closely the variations in the chemical composition of the gabbro. My friend, Mr. G. Barrow, of the Geological Survey of Scotland, has had the kindness to make a complete analysis of one selected specimen and a partial analysis of another. The former is an example of the quartz-bearing gabbro, though not actually the most acid rock found. The latter is the densest and most basic specimen obtained, having an extraordinarily large proportion of iron ores.

| | I. | II. |
|---|---|---|
| $SiO_2$ | 53·50 | 32·53 |
| $TiO_2$ | 0·45 | 5·30 |
| $Al_2O_3$ | 22·20 | |
| $Fe_2O_3$ | 3·60 | 8·44 |
| $FeO$ | 2·64 | 17·10 |
| $MnO$ | 0·35 | |
| $MgO$ | 2·00 | 7·92 |
| $CaO$ | 9·45 | |
| $Na_2O$ | 4·26 | |
| $K_2O$ | 0·61 | |
| Ignition | 1·50 | |
| | 100·59 | |
| Specific gravity | 2·800 | 3·265 |

I. Quartz-gabbro, by roadside, 150 yards N.N.W. of Chapel Stone. (The lime is probably a little too high.)

II. Iron-ore gabbro, upper part of Furthergill Sike.

[1] Zeitschr. für prakt. Geol. vol. i. (1893) pp. 4–11, 125–143, 257–284.

One point brought out by these analyses is that the augite, and the uralitic hornblende derived from it, must be rich in alumina. Another point of interest is that the iron ore is in a high degree titaniferous. If from the second analysis we calculate the iron ores as magnetite and ilmenite, the percentages of these are found to be 12·24 and 9·93 respectively, the two together thus constituting 22·17 per cent. of the whole rock.

Looking simply at the bulk-analyses, we observe that while analysis II. shows more than four times as much iron oxides as I., and nearly four times as much magnesia, it shows about twelve times as much titanic acid. In other words, regarding the second rock as a basic modification of the first, the titanic acid is much more strongly concentrated in the basic *facies* than the iron-oxides are. This is in agreement with what is recorded in other districts, such as those of Ekersund and Taberg. Vogt[1] remarks as characteristic of this type of modification ('oxidic' secretion of iron ores) that there is never less titanic acid than that corresponding to the relation Ti : Fe = 1 : 10, and often considerably more. In our rock the ratio is 1 : 5·3. As regards the other constituents, which were roughly estimated for the second rock, though exact figures are not given, analysis II., as compared with I., shows, in addition to the great falling off in silica, a very considerable reduction in lime, and a certain diminution in the percentage of soda, while the potash disappears almost entirely. Phosphoric acid has not been estimated, but the microscope shows that apatite, which is scarcely to be found in most specimens of the more acid varieties of the gabbro, becomes locally abundant in the highly basic marginal rocks. In all these particulars, the variation observed here resembles that recorded by Vogt and others in other parts of the world.

The Carrock Fell gabbro illustrates, then, a clearly characterized type of continuous variation in a single intrusive mass of basic rock, the variation being related in a simple manner to the boundary of the mass. It cannot be doubted that all the varieties have been derived by the differentiation of a single magma after its intrusion, and that such differentiation consisted in a concentration of what we may call the more basic constituents of the magma in the marginal parts. The phenomena thus afford an opportunity of bringing to the test some of the ideas that have been put forward with reference to the probable causes of differentiation in rock-magmas, and this I shall briefly attempt to do.

### 5. Discussion of the Causes of such Variation.

Several possible causes of differentiation have been suggested, and one or other of them may have been the chief cause in particular instances. In the present case the circumstances enable us to eliminate at once some of these suggestions. It may be remarked first that the concentration of the basic constituents is found along both the northern and the southern margin of the mass. These

[1] Zeitschr. für prakt. Geol. vol. i. (1893) p. 10.

probably represent the upper and lower sides of the intrusion as originally consolidated, but, whether this be so or not, the bilateral symmetry proves that gravity has not been the determining factor. This disposes, for the case under consideration, of the idea of a fluid magma becoming richer—in its lower strata—in the denser constituents; and also of the notion of the earlier formed crystals of iron ores, etc., sinking in the still fluid magma. If these processes have operated at all, they have produced effects only quite subordinate to the general differentiation observed. Again, Vogt has suggested that any inequality in the distribution of iron compounds in a molten magma, once set up, might be augmented by magnetic attraction. This idea is propounded apparently with reference to a central rather than a marginal concentration of iron ores in a magma, and moreover it could not account for the observed concentration of other constituents, such as phosphoric acid. In view of the fact that natural magnetite loses its magnetic property completely when heated to 557° C., it does not seem likely that magnetic attractions can play any part in the equilibrium of a molten rock-magma, and I shall accordingly discard this suggestion.

The only possible causes of differentiation that remain in the case under consideration are those which depend on the difference of temperature between the central and marginal parts of the magma while still fluid or partly fluid; and the concentration of the iron, etc., towards what were the cooling surfaces of the mass seems to point directly to the influence of this factor. In what way this influence took effect is a question requiring some discussion.

Most writers who have speculated on the mode of origin of a heterogeneous rock-complex by differentiation of a magma originally of uniform composition, have based their conception of the nature of the magma on its analogy with an ordinary saline solution. Lagorio[1] apparently considers that one or more definite silicate-compounds ($R_2O$ $2\,SiO_2$, etc.), which he terms '*Normalglas*,' act as solvent for all the other constituents. It is not easy to reconcile this view with the existence of a very fairly constant order of crystallization for the several minerals. For instance, however little phosphoric acid and however much of the iron oxides a magma contains, apatite seems to crystallize out invariably before magnetite or iron-bearing silicates; and, in general, the order of crystallization depends little, if at all, upon the relative amounts of the several constituents contained in the magma. As an alternative to Lagorio's idea of a single general solvent, we might perhaps imagine that a constituent on the point of crystallizing out is then the dissolved substance, the remaining fluid magma as a whole being the solvent. Some such idea seems to be intended by some authors who have not very clearly defined their view of an igneous rock-magma as a solution.

Now, it follows from the theory of osmotic pressure that if different parts of a simple saline solution be at different temperatures, the concentration must also vary, and equilibrium will be established

[1] Tscherm. Min. u. Petr. Mitth. vol. viii. (1887) pp. 507, 508.

only when the concentration at every point is inversely proportional to the absolute temperature. Soret has demonstrated experimentally the greater concentration of the salt in the cooler part of the solution. This law, known as 'Soret's principle,' has been applied by Lagorio, Teall, Brögger, Vogt, Iddings, and others, to the case of an igneous rock-magma regarded as a solution. In particular, the relative richness of the marginal parts of an intrusive mass in the more basic minerals has been explained as due to the concentration of the less soluble constituents of the magma, while still fluid, in the cooler region.

On this point one or two remarks may be made. In the first place, the idea cannot be entertained at all in connexion with Lagorio's theory of a single general solvent. As Bäckström [1] has pointed out, differences of temperature could not, on that hypothesis, alter the *relative* concentration of different dissolved constituents. We are therefore driven to some less precise and more complex view of the nature of the 'solution' in a rock-magma. Supposing, however, that something analogous to Soret's principle still holds, we may enquire whether this is adequate to explain the degree of concentration actually observed in the case of the Carrock Fell gabbro. The precise law arrived at by van't Hoff, identical with the law for gases, states that, in the condition of equilibrium, the concentration of the dissolved substance varies inversely as the absolute temperature. Now, in our case, the amount of iron ores in the rocks at the margin of the mass is at least twenty-five times the amount in the rocks at the centre; but it is manifestly impossible that the absolute temperature of the magma at its centre could ever be twenty-five times, or even five times, that at its margin. The explanation is clearly insufficient to account for the facts.[2]

It must be understood that I speak here of differentiation effected *in situ* in a magma, which may fairly be assumed to have been of uniform composition when intruded into its surroundings. We are not, in this case, concerned with *successive* differentiations of magmas and partial magmas amidst new surroundings, as conceived by Iddings, or as described by Brögger. On any solution-hypothesis of rock-magmas, Soret's principle does not afford an explanation of the variations observed in the Carrock Fell gabbro. Further, I question how far that principle, which holds good for dilute solutions, can throw light on the physics of a rock-magma near the point of crystallization, which must be compared with a nearly saturated solution.

The phenomena of differentiation described by Prof. Brögger in the eruptive rocks of the Christiania basin, and especially in those of the Gran district,[3] differ in a fundamental respect from

[1] Journ. of Geol. vol. i. (1893) p. 774. The author, however, does not limit his criticism, as is here done, to this particular view of the solvent medium.

[2] This argument has been advanced by me in a brief note: Geol. Mag. 1893, pp. 546, 547.

[3] Quart. Journ. Geol. Soc. vol. l. (1894) pp. 15–37.

those described above at Carrock Fell. Brögger points out that in his area rocks genetically connected may differ widely in *mineralogical* as well as in chemical composition. Thus, in his olivine-gabbro-diabase, the ferromagnesian minerals are pyroxene, olivine, and biotite; in the camptonite, which is an offshoot of it, brown hornblende largely predominates. He justly concludes that differentiation has "taken place in a liquid magma, even before crystallization of any importance had begun." In the Carrock Fell gabbro the case is quite different. Here the different varieties of the rock consist invariably of the *same minerals*, only in different relative amounts.[1] I have already remarked that the felspar is of the same variety in almost the whole of the rocks examined. If the differentiation of the magma had been completed prior to any crystallization, we should expect different parts of the magma to have given birth to different varieties of felspar. The complete want of olivine, even in the ultrabasic varieties of the rock, is another fact that would be difficult to explain on the hypothesis that the magma was differentiated first and then crystallized; and indeed such a sequence of events seems to be quite inconsistent with the phenomena that I have described. On the other hand, to suppose that the differentiation was brought about by a migration of minerals already crystallized out would raise obvious difficulties. No cause can be imagined to produce such a movement of crystals to the margin of the reservoir. The only alternative is to suppose that the differentiation took place by diffusion in a fluid magma, but not as a process distinct from and quite anterior to crystallization. It was, as I believe, effected in a quasi-saturated magma concurrently with the crystallization of the earlier-formed minerals.

The remarks just made apply, as stated, to the particular case under discussion, but it seems probable that many of the examples of differentiation recorded by Vogt and others will fall under the same head. The characteristic of all is that the several constituents are *concentrated in a definite order, which is identical with the order in which they crystallize out from the magma* (Rosenbusch's "order of decreasing basicity"). The concentration is greatest for the minerals belonging to the earliest stage of crystallization, viz. apatite, ilmenite, magnetite, etc. The minerals of the second stage, the ferromagnesian silicates, are less strongly concentrated. In such cases, when differentiation apparently "has been determined by, and is dependent on, the laws of crystallization in a magma," it seems reasonable to seek the cause of differentiation in the crystallization itself.

The conditions introduced by this simple hypothesis have no analogy with those of a dilute solution; and, though we may conveniently employ the terminology of solutions in speaking of it, it does not follow that we need frame any precise theory of the nature of an igneous rock-magma. The process of differentiation is brought

[1] Quartz and orthoclase are wanting altogether in the most basic varieties, but these, being the very latest products of consolidation, do not enter into the argument.

at once under the perfectly general principle of the degradation of energy. In whatever form the elements of a given mineral exist in the fluid magma, it cannot be doubted that the crystallization of the mineral from the magma involves in every case a very considerable evolution of heat. Hence whatever promotes crystallization in the magma will tend to the most rapid degradation of energy. When crystallization has already begun in one region of the magma, this result will be attained by a determination of that constituent with which the fluid is most easily saturated to that region of the magma which is already on the point of saturation. The region of the magma which first becomes saturated with a certain constituent will therefore, as crystallization proceeds, have its saturation maintained by diffusion at the expense of the rest of the magma. It is evident that, as a perfectly fluid magma cools down, the point of saturation, say with apatite (or with phosphoric acid), will be reached first in the margin of the body of magma, that being the coolest region and also, if the Soret action has already set up heterogeneity, the region of greatest concentration of the substance in question in the fluid magma. Apatite begins to crystallize out at the cooling surface of the magma, and diffusion maintains the saturation and crystallization in this the coolest region. Ilmenite and magnetite follow, and in turn the ferromagnesian silicates. But there will evidently be a tendency towards restoring temperature-equilibrium between the margin and the interior, and, what is more important, with falling temperature and increasing acidity the residual magma becomes so viscous that diffusion is more and more checked, and finally ceases. Thus the concentration towards the cooling surface is strongest for the first-formed minerals, and continually feebler for those which follow, according to their order of succession.

It seems, then, that the intimate relation between the phenomena of concentration and of crystallization, which has been remarked by several writers, leads to a simple explanation of the concentration of certain constituents in the marginal parts of a rock-mass; and from this explanation the fact that the order of concentration of the several constituents is also the order of their crystallization follows as a necessary corollary. Further, there is here no narrow limitation of the possible degree of concentration, such as that which the law of osmotic pressure imposes upon the Soret action. There is no difficulty, for instance, in admitting that a pure aggregate of ilmenite may segregate from a rock-magma. According to 'Soret's principle,' this would imply an infinite degree of concentration, corresponding to absolute zero of temperature!

There is, however, one consideration that must not be passed over without notice. Bäckström[1] asserts that "a silicate magma during its period of crystallization is certainly too viscous to permit of any considerable diffusion." It does not appear on what evidence this statement rests. The petrographical features which most clearly point to high viscosity are connected especially with

[1] Journ. of Geol. vol. i. (1893) p. 773.

the later stages of consolidation in acid lavas : while the phenomena of differentiation are most strikingly exhibited in the earlier stages of consolidation of basic intrusive rocks. The best experimental results bearing on the question are those of Vogt,[1] obtained from artificial slags having the general composition of igneous rocks. Any differences that exist between the conditions in the artificial and the natural magmas will probably tend to lower the viscosity in the latter, which may be expected to contain a certain amount of water in all cases, and sometimes other fluxes ('agents minéralisateurs'). Vogt found viscosity to be in direct relation to acidity, the results differing widely for extreme cases. At the same moderate temperature-distance above their respective melting-points, strongly basic slags flow like water, while strongly acid ones are as stiff as tar. The 'melting-point' of a rock-magma is not a term of precision; but, so far as our knowledge goes, it seems highly probable that diffusion can proceed freely during the earliest stage of crystallization in a basic rock-magma, being, however, checked more and more as the temperature falls.

## 6. Some Deductions from the Phenomena.

I have dealt rather fully with the gradual variation of the gabbro from centre to margin, because the results, if they are considered to be established, bear upon theoretical questions which have lately attracted much attention. But these results also have very direct consequences for the particular area under discussion, leading to certain definite conclusions as to the geological relations of this gabbro intrusion, and enabling us to discard confidently certain suggestions that have been made under this head. Similar reasonings will be applicable to other masses of igneous rocks showing a like type of differentiation. The several points are sufficiently obvious to be treated summarily.

Firstly, then, the gabbro is a true igneous rock. The whole body of it was at one time fluid enough to admit of the freest movement among its parts, and that too *while all the surrounding rocks were cool.* This consideration, we think, is enough to dispose of the theory of Mr. Ward,[2] that the gabbro has been produced by extreme metamorphism of the volcanic rocks. Chemical and other facts equally militate against such a hypothesis.

Next, we see that the gabbro mass does not represent any portion of a duct of a volcano, but is an intrusion of laccolitic type. The magma was injected among cool rocks, and there consolidated. Had there been any prolonged flow of molten matter, the surrounding rocks must have become heated, and the mass that finally

[1] Zeitschr. für prakt. Geol. vol. i. (1893) p. 275.

[2] Ward quotes from Sedgwick a passage in the same general sense, though offered merely 'as a conjecture' (Third Letter to Wordsworth, 1842). J. G. Marshall maintained the Carrock Fell rocks, with all the chief igneous masses of the Lake District, to be of metamorphic origin (Report Brit. Assoc. 1858, Trans. Sect. p. 84.)

plugged the channel would have consolidated without the conditions necessary for the kind of differentiation described. Indeed we may take it as a general rule that the duct of a volcano is characterized by very considerable *everse*, but an absence of *inverse* metamorphism.[1] In the present case the form of the intrusive body and the manner in which the volcanic rocks follow their strike undisturbed through the heart of the gabbro also indicate unmistakably the nature of the intrusion.

Again, the alleged passage from the gabbro to the granophyre is seen to have no real existence, at least so far as concerns the phenomena in the former rock. That modification of the gabbro which in some petrographical features approaches the acid rock, forms the heart of the gabbro mass, while that in actual contact with the granophyre is of a highly basic variety. I propose to consider the question again from the side of the granophyre, but it is quite clear that the two rocks represent two distinct and successive intrusions. This is, of course, quite consistent with the possibility of the two magmas having been derived from different portions of one deep-seated reservoir.

Finally, I cannot accept Prof. Sollas's suggestion[2] that the micropegmatite of the quartz-gabbro is due to an injection of solid gabbro by the granophyre magma. There are certainly veins of granophyre penetrating the gabbro, and locally numerous, but these are never on the microscopic scale described by Prof. Sollas at Barnavarve, and the orderly disposition of the various types of gabbro in the Carrock Fell intrusion would be unintelligible on the injection hypothesis. I shall have to speak later of the possibility of intermediate rocks originating by the admixture of acid with basic, in a somewhat different manner, but I do not believe that the idea is capable of any very wide extension.

These conclusions seem to follow fairly from the phenomena of differentiation described, though they can be fortified by other considerations. I wish to point out, however, that these phenomena may sometimes lead to conclusions which could not otherwise be reached; so that a careful survey of an igneous mass by chemical tests, or simply by specific gravities, may give definite information regarding the field-geology of the district. Thus, the separation of the areas which we have distinguished as gabbro and diabase comes out distinctly in this way, the zone of basic rock which bounds the gabbro area on the side of the granophyre being evidently prolonged westward by Round Knott. When thus divided, the relative age of the two rocks can be decided. It might, of course, be conjectured plausibly that, since veins of granophyre are abundant in the gabbro and wanting in the diabase, the one rock is older and the other

[1] These terms, due to Morlot, besides having priority, seem to be more pointed and less clumsy than their equivalents 'exomorphic and endomorphic,' or 'exogenous and endogenous,' used by some German and French writers.

[2] Geol. Mag. 1893, pp. 551, 552. [Subsequently elaborated in Trans. Roy. Irish Acad. vol. xxx. (1894) pp. 477–512.]

newer than the acid intrusion[1]; but the way in which the gabbro is differentiated affords at least as strong an argument in the same direction. It is noteworthy that, so far as the few observations of specific gravity go, the diabase seems to be much more uniform than the gabbro, as if the requisite condition for differentiation, namely, cool encasing walls, had been wanting in the case of the later intrusion.

Again, if the basic margin may be taken as marking with tolerable uniformity the original boundary of the gabbro mass, its completeness or otherwise will give information with respect to subsequent accidents which may have affected it. The presence of a basic border on the south side of the intrusion may be taken as indicating that very little of the gabbro is lost in consequence of the bounding fault. On the northern boundary some irregularities occur which suggest that portions of the basic margin of the mass may have been carried away by the later intrusion of granophyre, and I shall have occasion later to notice phenomena in the latter rock which fully accord with this idea. Again, the narrowing of the outcrop of the more acid type of gabbro towards the east seems to point to a termination of the intrusive mass in that direction, so that no fault would be required to account for the non-appearance of the gabbro on the other side of the valley alluvium. As regards the westward termination of the intrusion, the country there is much concealed by peat-mosses, but the thoroughly basic character of the gabbro seen in Roughten Gill and in Brandy Gill[2] may perhaps point to a coming together of the northern and southern boundaries of the original intrusive body, which is broken into by considerable masses of granophyric rocks.

### 7. Reactions between Gabbro and Enclosed Masses of Lava.

There remain to be briefly noticed certain special modifications of the gabbro which are of an entirely different order from those described above, being local or 'contact'-phenomena. As already mentioned, some of these peculiarities are connected with the enclosed patches of volcanic rocks, others with the proximity of the large granophyre intrusion. Only the former will be treated at length in this place.

I have stated that the masses of basic lava enveloped by the gabbro are readily identified as members of the Eycott Hill group, the typical locality for which is less than 3 miles distant. The rocks are nevertheless very considerably metamorphosed, and the gabbro in their immediate vicinity shows certain signs of inverse metamorphism. The lavas as they occur at Eycott Hill were briefly described by Mr. Clifton Ward,[3] who gave chemical analyses

[1] I have found no actual exposure of the contact of granophyre and diabase *in situ*, but junction-specimens of the two rocks occur among the loose blocks to the north of Great Lingy, and in these the diabase takes on a very fine-grained texture.

[2] Specific gravities: Roughten Gill 3·113, Brandy Gill 3·065.

[3] Monthly Microsc. Journ. vol. xvii. (1877) pp. 239–246.

showing from 51·1 to 53·3 per cent. of silica. Prof. Bonney[1] pointed out the occurrence in these rocks of an altered rhombic pyroxene. Mr. Teall[2] has given an account of one of the most remarkable flows. The characteristic features are the occurrence of large porphyritic crystals of a lime-soda felspar, frequently rounded and having peculiar inclusions, and the abundance in the groundmass of magnetite and pseudomorphs after hypersthene. The metamorphosed lavas enclosed in the Carrock Fell gabbro have a fresh aspect and a high density, the specific gravities of the conspicuously porphyritic and the more compact types being 2·835 and 2·887, as compared with 2·754 and 2·744 at Eycott Hill. The groundmass has become darker and more lustrous, and the large felspars have a clearer appearance, though not otherwise altered to the eye. Under the microscope it is seen that these felspars have for the most part lost their conspicuous inclusions in the form of negative crystals, but the crystals usually retain their identity, and show their albite- and Carlsbad-twinning unaltered. Only occasionally have they been recrystallized into a new mosaic [1550] in the fashion that we have noticed in the basic lavas bordering the Shap granite. The serpentinous or bastite-pseudomorphs after hypersthene have been converted into a very pale, greenish amphibole of rather fibrous structure. Possibly some of this mineral may represent the original augite of the lava or its decomposition-products, but the metamorphosed examples sometimes contain fresh augite [1549, etc.]. The little twinned felspars of the groundmass resemble those of the unaltered rocks, except in a greater freshness and clearness, which could scarcely be interpreted as conclusive evidence of recrystallization, but they sometimes appear to fit together in the manner characteristic of metamorphosed rocks. The magnetite seems to be on the whole in better octahedra than in the unaltered lavas. But what points more unmistakably to some degree of recrystallization in the groundmass is the disappearance in the most altered rocks of the isotropic base.

So far I have noticed familiar, and not even extreme effects of thermal metamorphism in basic lavas.[3] There are, however, at the actual junction of the lava with the gabbro, phenomena more unusual, involving reciprocal modifications in the two rocks. I have said that the line of junction can be shown in a thin slice under the microscope, but it is often a curiously irregular line; and the plexus of small felspar-prisms, which constitutes a large part of the groundmass of the lava, has been, so to speak, 'teased out' at the edge, so that scattered prisms lie a little beyond what

[1] Geol. Mag. 1885, pp. 76–80.

[2] 'British Petrography' 1888, pp. 225–227. For a notice of the same lavas as seen at Melmerby, across the Eden valley, see Quart. Journ. Geol. Soc. vol. xlvii. (1891) p. 517.

[3] Some of the lavas, on the southern edge of the gabbro, show a different type of metamorphism, and especially the development of abundant red garnets. These phenomena, which are found in very many parts of the Lake District, have, I believe, no direct connexion with the gabbro intrusion, and they will not be further referred to in this place.

must be regarded as the true line of junction. These scattered prisms of plagioclase are embedded in a perfectly clear mosaic of moderately coarse texture, which seems to be in some cases of quartz, in others of felspar, mostly untwinned. The structure is thus that which G. H. Williams[1] has termed 'micro-poikilitic.' The general appearance is as if the felspars had been set free, by what was originally the isotropic base of the lava becoming dissolved and absorbed into the gabbro-magma. The material thus taken up is doubtless represented in part by the brown mica which we find in the neighbouring gabbro, but the quartz and the (probably acid) felspar of the clear mosaic are perhaps to be referred to the same source. Mica is developed only exceptionally in the metamorphosed lava, and has somewhat different characters from that in the gabbro. Its pleochroism is from a rich brown to colourless, and there are intensely pleochroic haloes around certain inclusions too minute for identification [1549].

Certain narrow veins, conspicuous in hand-specimens, pass from the gabbro-junction into the lava, and contain especially idiomorphic brown hornblende moulded by quartz [1626]. Again the micro-poikilitic areas may take on the form of little veins extending into the lava [1553], or these may anastomose and spread for a short distance from the junction. Indeed, the groundmass of the lava very near to the gabbro seems locally to be replaced by patches of clear quartz, etc., wedged in among the porphyritic felspars, the needles of apatite, and the pyroxenes or their representatives [1625, etc.]. Both pyroxene and magnetite seem in some places to have been absorbed.

It must be concluded from these phenomena that the gabbro-magma has to some extent corroded away and incorporated in itself the glassy base of the lava, and even in places some of its minerals, in the immediate neighbourhood of the junction. Nevertheless all the facts go to negative the idea that the lava has been to any important extent melted down by the gabbro-magma. The felspars have not apparently been dissolved at all. Even the little prisms remarked as occurring outside the line of junction show no rounding or diminution in size, and since they do not occur to any greater distance than a fraction of an inch, it seems that very little of the rock can have been removed. The blocks of lava, and the fragments into which they are divided by veins of gabbro, are sharply angular.

The same inference might be drawn from an examination of the gabbro near its junction with the lavas. The rock here, and for a few feet, always contains brown mica, a mineral foreign to the normal gabbro. The mica, indeed, occurs nowhere else in the mass, with an exception to be noted below. At one or two spots where the mineral was noticed no lava was actually exposed, but these places were on the line of strike of the Eycott group as seen not far away, and doubtless mark the position of concealed patches of lava.

[1] Journ. of Geol. vol. i. (1893) p. 176.

If it be granted that the mica in the gabbro is a phenomenon of inverse contact-metamorphism, due to the absorption of a certain portion of the enclosed lava by the gabbro-magma, an interesting conclusion follows. It is clear that if such absorption had taken place soon after the intrusion of the gabbro-magma, when that magma was fluid enough, as we have seen, to permit free diffusion throughout, the brown mica could not have been restricted, as it is, to the immediate neighbourhood of the lava. The action must therefore belong to a later stage, when the magma had attained a considerable degree of viscosity, and must be connected with the growing *acidity* of the magma in its central region due to concentration of the basic constituents in the marginal parts. In point of fact, it is in the quartz-bearing varieties of the gabbro that these phenomena of inverse metamorphism are observed.

## 8. Conclusion.

The last kind of modification of the gabbro to be noticed is seen near the northern edge of the mass, at Furthergill and westward. On comparing the dense iron-ore gabbros along this strip with those on the southern border of the mass, certain peculiarities are observed which can only be referred to the proximity of the large body of granophyre intruded at a later time, when the gabbro was solid.

Some of these peculiarities may be considered simply as phenomena of metamorphism produced by the heat of the later intrusion. Thus, instead of the usual uralitic alteration of the augite, we find that mineral passing in a capricious fashion into a compact brown hornblende, which probably indicates some absorption of iron oxide from the ilmenite. Granular sphene has arisen probably from reaction between the ilmenite and the felspar [1866]. The felspar is much broken up into secondary minerals, among which specks of a pale amphibole are conspicuous as well as chloritic substances. Pale fibrous amphibole sometimes forms a fringe in crystallographic relation with augite, but evidently occupying the place of felspar [1525]. There are large patches consisting essentially of matted tremolite-fibres, the origin of which is not clear. With this may be associated a little brown mica [1536], while small patches of this or of a deep brown hornblende have formed characteristically about some of the grains of iron ore. The various changes observed, or at least some of them, point to thermal metamorphism of the gabbro by the granophyre. (See also Pl. XVII. fig. 4, and explanation.)

The rocks showing the above features may be regarded as the margin of the gabbro proper. They are immediately succeeded by rocks of a very remarkable character, which form a zone running up Furthergill and onward nearly to Round Knott, dividing the gabbro from the granophyre. Along this zone the gabbro has been in great part actually re-fused, and has crystallized again as a rock of strikingly coarse texture, with large idiomorphic felspars and large well-built crystals of hornblende. The granophyre

magma, mingling with the fused ultrabasic gabbro, has given rise to abundant micropegmatite, the appearance of which in a rock so rich in iron ores is very remarkable.[1] Beyond this zone of rocks are others produced by the incorporation of molten ultrabasic gabbro into the granophyre magma, but these varieties and the general relations between the gabbro and the granophyre will be more properly discussed in connexion with the latter rock. It will be noticed that the production of chemically intermediate rocks at the junction of a basic and an acid rock, as here recognized, has no resemblance to the injection of solid gabbro by minute veins of granophyre, as described by Prof. Sollas; but phenomena comparable with those which he has described are also locally found. (See Pl. XVII. fig. 6, and explanation.)

The rocks distinguished at the outset as diabase will not be more fully described. Mineralogically they resemble the gabbro, and they reproduce in a less marked manner some of the same phenomena of variation. They have certain special points of interest, but not connected with the subject in hand. The present paper deals specially with the variations exhibited in the large gabbro intrusion. I hope on another occasion to show that the Carrock Fell granophyre also exhibits considerable variations, due to another cause, and that the Grainsgill greisen is the result of a process of differentiation entirely distinct from that discussed in the case of the gabbro.

## EXPLANATION OF THE PLATES.

### Plate XVI.

Sketch-map of part of the Carrock Fell district, showing variation of gabbro. (Scale: 6 inches = 1 mile).

An attempt is made here to show the distribution of the several varieties of gabbro and diabase. The criterion used is the specific gravity of the rocks, and the data are shown by figures on the map. These are chiefly in the eastern part of the gabbro area, and the dividing lines farther west are drawn with reference to the general characters of the rocks judged by eye and checked by a certain number of specific-gravity determinations, as shown. The specific gravity of the gabbro is seen to increase rapidly from the central zone to either margin. The rock here termed diabase shows much less variation.

The remarkable relations between the gabbro and the granophyre are not shown in detail, and the numerous dykes and veins are not marked.

The general distribution of the enclosed masses of Eycott lavas is roughly indicated. It would be impossible to represent accurately the intricate relation between these volcanic rocks and the enveloping gabbro.

### Plate XVII.

*Note.*—The figures are magnified 20 diameters, and, except no. 2, are drawn in natural light. The numbers in brackets refer to the slides, which are in the Woodwardian Museum, Cambridge.

Fig. 1. [79]. Gabbro, White Crags (from Mr. Ward's collection). This shows the dominant pyroxene, an augite with fine lamellation parallel to the basal plane. This is combined with simple twinning parallel to the orthopinacoid, giving the 'herring-bone' structure. The augite is seen to mould the felspar-crystals. See p. 317.

[1] No chemical analysis of this rock has yet been made. The specific gravity of one specimen was as high as 3·122.

Fig. 2. [1867]. Gabbro, Iron Crags, about 200 yards W.N.W. of the sheepfold. This is drawn with polarized light (crossed nicols) to show what seems to be secondary twin-lamellation on both the albite- and the pericline-law in the plagioclase. In one part of the crystal the pericline-twinning affects only alternate albite-lamellæ. Other crystals in this slide show albite-lamellation in evident relation to the strain attending flexure. The dark line is a crack in the slice. See p. 316.

Fig. 3. [1874]. Gabbro, top of White Crags. The figure shows idiomorphic crystals of plagioclase moulded by a shapeless plate of more uniformly turbid, untwinned orthoclase, well seen in the upper part of the drawing. Lower, and to the left, is an interstitial patch of micropegmatite, in which the felspathic constituent is probably also orthoclase. Pyroxenes and iron ores do not appear in the portion of the slice figured. See p. 318.

Fig. 4. [2046]. Metamorphosed gabbro, Brandy Gill, 50 yards north of the upper 'Bield.' This is a very basic marginal variety of the rock, unusually rich in prisms of apatite, which are seen in abundance. The rock is profoundly modified by thermal metamorphism, the pyroxene being wholly transformed, partly into green actinolitic hornblende, partly into matted patches of brown mica-scales. The latter mineral occurs characteristically in the neighbourhood of the grains of iron ore, from which it has probably taken up some ferrous oxide and titanic acid. The clear grains in the lower right-hand part of the figure are portions of one crystal of felspar, divided by narrow veins now consisting of brown mica. The clearness of the felspar seems to be a characteristic of the metamorphosed gabbros. See p. 334.

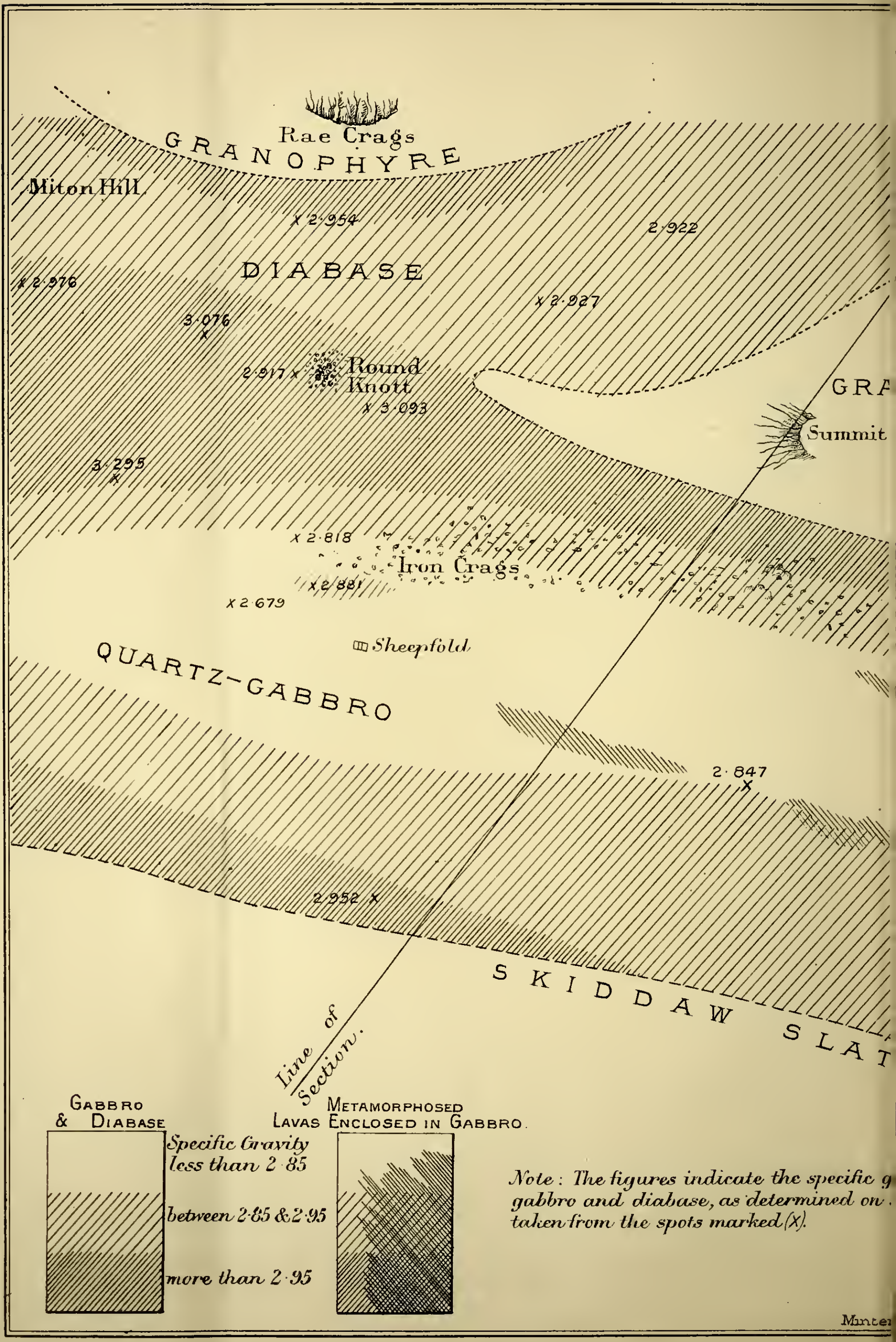
Fig. 5. [1526 and 1866]. Grains of iron ores in the gabbro. The example on the right, from the upper part of Furthergill Sike, shows irregular patches of magnetite (black) and ilmenite (grey). That on the left, from near the top of the same sike, shows the two minerals forming parts of one idiomorphic crystal, the dividing line being parallel to a crystal-boundary. See p. 318.

Fig. 6. [1622]. Modified Gabbro, crags in upper part of Furthergill Sike. This is from the actual margin of the gabbro, and is a highly basic variety, of specific gravity 3·122, rich in apatite (see upper part of figure). Nevertheless it contains quartz and micropegmatite (lower part of figure). This is probably due to an injection of the already consolidated gabbro by the later granophyre-magma, in the manner described by Prof. Sollas. At Carrock Fell this action seems to be exceptional, and is confined to the immediate contact of the two intrusions. Other parts of this slide and other specimens of the same rock show various phenomena of thermal metamorphism in the gabbro. See p. 335.

## Discussion.

Mr. Marr believed that the age of the gabbro intrusion had yet to be determined. The Author's work had for ever set at rest the idea that the gabbro had been formed by alteration of the volcanic rocks of the Eycott group; for the proofs of intrusion of the gabbro into these were complete. The mode of occurrence of the gabbro and granophyre reminded him of the description of masses of these rocks in Scotland, about which the Society had recently heard much. These were points of local interest, but the main object of the paper was to describe the variation in the different parts of the gabbro mass, and from what he had seen of the district he believed that the Author had established his points.

Prof. Judd congratulated the Author of the paper on taking up this



Rae Crags
GRANOPHYRE
Miton Hill
x 2·954
2·922
DIABASE
x 2·976
x 2·927
3·076
2·917 x
Round Knott
x 3·093
GRA
Summit
3·295
x 2·818
Iron Crags
x 2·881
x 2·679
Sheepfold
QUARTZ-GABBRO
2·847
2·952 x
SKIDDAW SLAT
Line of Section.
GABBRO & DIABASE
Specific Gravity less than 2·85
between 2·85 & 2·95
more than 2·95
METAMORPHOSED LAVAS ENCLOSED IN GABBRO.
Note: The figures indicate the specific g
gabbro and diabase, as determined on
taken from the spots marked (X).
Minter


SKETCH-MAP OF PART OF THE
CARROCK FELL DISTRICT.
SHEWING VARIATION OF GABBRO.
by Alfred Harker, M.A., F.G.S.
SCALE: 6 INCHES TO A MILE.
0 50 100 200 300 400 500 YARDS.
South
OPHYRE
Pike
Sheepfold
Furthergill Sike
ALLUVIUM.
x 3·200
3·222 x
2·941 3·060
x 3·265
x 2·848
White Crags.
QUARTZ-GABBRO
2·850 x
Crag East
x 2·833
x 2·800
2·822
2·821
x 2·778
Buck Kirk
x 2·890
2·844 x
2·888
2·877
Sheepfold
2·931
2·939
S
2·983
Snailshell Crag
x 2·872
2·922
Black Crag
3·042
3·110
Sheepfold
3·103
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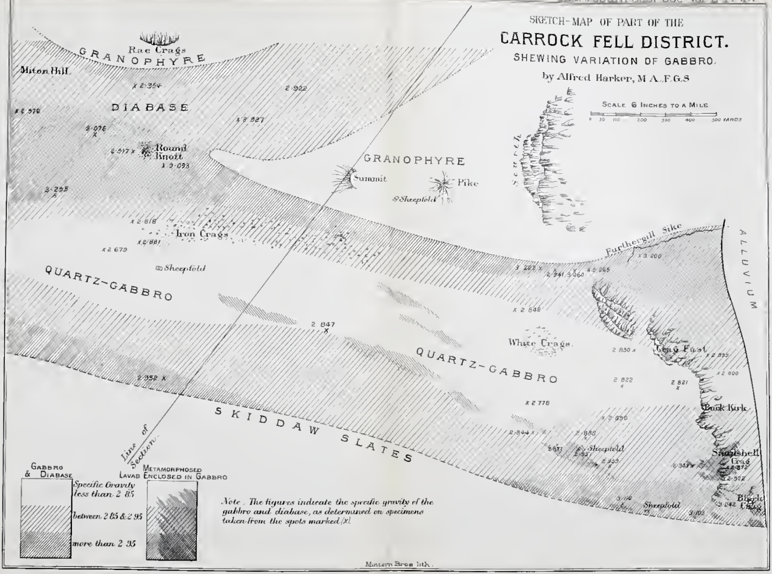
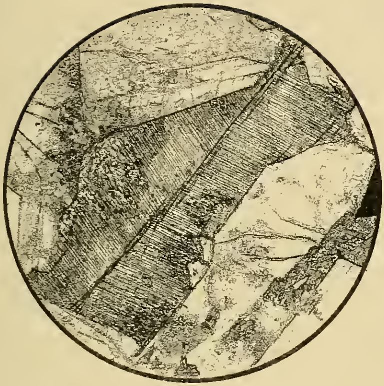

SKETCH-MAP OF PART OF THE
CARROCK FELL DISTRICT.
SHEWING VARIATION OF GABBRO.
by Alfred Harker, M.A., F.G.S.
SCALE 6 INCHES TO A MILE
0 50 100 200 300 400 500 YARDS
Rae Crags
GRANOPHYRE
Miton Hill
DIABASE
Round Knott
GRANOPHYRE
Summit
Pike
Sheepfold
Scree
Iron Crags
Sheepfold
QUARTZ-GABBRO
Furthergill Sike
ALLUVIUM
White Crags
QUARTZ-GABBRO
Crag Fast
Buck Kirk
SKIDDAW SLATES
Snailshell Crag
Sheepfold
Sheepfold
Black Crag
Line of Section
Gabbro & Diabase
Metamorphosed Lavas Enclosed in Gabbro
Specific Gravity less than 2.85
between 2.85 & 2.95
more than 2.95
Note. The figures indicate the specific gravity of the gabbro and diabase, as determined on specimens taken from the spots marked (x).
Mintern Bros. lith.

1



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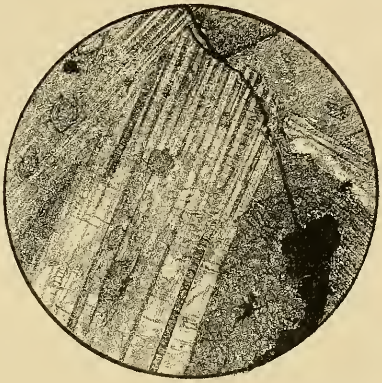

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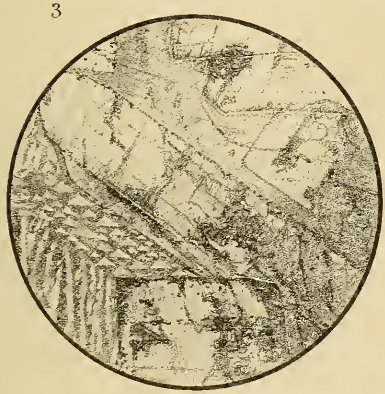

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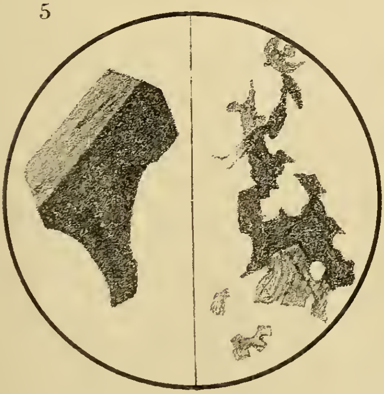

6.

A. Harker del. F. H. Michael lith. Mintern Bros. imp.

CARROCK FELL GABBRO.

highly interesting district of Carrock Fell as a subject of study. He bore testimony to the careful investigation of the area by the late Clifton Ward. The Author's observations seemed to show that concentration by crystallizing processes might go on in a mass of large dimensions, as well as in dykes like those described by Lawson and Vogt.

Prof. Cole expressed the regret which all must feel that Prof. Sollas could not be present to join in the discussion. The parallelism of the so-called granophyre and the several layers of the basic rocks seemed to suggest that the whole Carrock Fell mass might be a huge composite dyke, the acid rock having intruded into the gabbro distinctly on the north, and farther south as a plexus of minute interpenetrations along the central line of the gabbro, giving rise there to the gabbro with micropegmatitic groundmass. The microscopic sections seemed to him to support this view, by reason of the contrast between the basic areas and the patches of micropegmatite. The aggregation of iron ores on the margins of the gabbro must, however, be explained by some such theory as that which the Author had put forward.

Mr. Rutley considered that one of the most interesting points in this valuable paper was the occurrence of lavas of the Eycott series in the gabbro. How portions of lava-flows should become embedded in a plutonic rock was a problem which seemed to need further elucidation. The question whether the more acid character of the central portion of the gabbro was due to differentiation of the original magma, or to incorporation, by fusion, of apophyses from the adjacent granitic rock, was an open one; but it seemed probable that, if the latter hypothesis were the true one, the alteration, where the gabbro was seen to come into contact with the granitic rock, should extend over a wider area than that represented in the section.

The Author thanked those who had spoken for their remarks. In reply to Prof. Cole, he said that, while believing in a probable genetic relationship between the granophyre and the gabbro, he did not think that the injection-theory of Prof. Sollas afforded any explanation of the regular distribution of the more or less acid varieties of the gabbro.

Replying to Mr. Rutley, he described the occurrence of the masses of Eycott lavas enclosed in and intricately veined by the gabbro, but always with a sharply defined junction. All the phenomena negatived the hypothesis of a metamorphic origin for the latter rock.